Choosing the right VHF data link technology for commercial aviation air traffic services

by

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Abstract

Choosing the right VHF data link technology for commercial aviation air traffic services.

Thesis directed by Dr. Harvey Gates.

The Very High Frequency (VHF) Amplitude Modulation (AM) channel used for voice communications among air traffic control and commercial airline pilots is congested. This contributes to National Airspace System (NAS) system inefficiencies such as aircraft delays, diminishing airline profits and most importantly a compromise in the safety of passengers and flight crew. Although there are elaborate data linking designs in progress to address these problems through concepts such as Free Flight, Satellite-based Air Traffic Management Systems, etc., it could be years before a data link is implemented. Because a data linking solution is critical to the safety and efficiency of airline operations, VHF data link (VDL) technology should be immediately implemented to provide effective and reliable communications between pilots and air traffic controllers.

The three competing digital data link technologies are VDL modes 2, 3 & 4. VDL mode 2 and mode 3 are considered to be primarily communications solutions while VDL mode 4 also offers surveillance capabilities. First, VDL mode 2 provides a data rate that is ten (10) times faster than the current ACARS system; however, it uses the carrier sense multiple access (CDMA) protocol to access the channel. Second, VDL mode

3 (NEXCOM) has the ability to transmit and receive digital voice and data through the time division multiple access protocol (TDMA). However, if it were to transmit data exclusively, it would use the CSMA protocol. Lastly, VDL mode 4 provides digital data as well as provides a built-in surveillance capability. It uses the self-organized time division multiple access (STDMA) protocol to access the media, which is more efficient than CSMA for channel access. Also, it's surveillance capabilities allow future air traffic initiatives such as Free Flight to be seamlessly accommodated. Consequently, VDL mode 4's should be considered as the right data link technology for commercial aviation air traffic services.

Dedication

This thesis is dedicated to the memory of those pilots and families of September 11, 2001 who paid the ultimately price by surrendering their lives for our freedom; and to my wife and friend Ramona who supported me with her love and patience through this long and windy academic pursuit by gently encouraging me and giving me distance from reality by running our house-hold. Lastly, to my Lord for his providence and divine guidance.

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The Department of Commerce's, Chris Behm, Dr. Margaret Luebs and Dr. Rob Stafford who provided feedback and editorial comments on specific sections of this document. Mr. Evan Darby whose outstanding public service should be a model for all to follow at the Federal Aviation Administration William J. Hughes Technical Center. His correspondence over the past four months has provided me with a real-time understanding of the data link communication initiatives. Also, Mr. Theo Hendriks, Mr. Daniel Daems and Mr. Luca Dell'Orto from Eurocontrol offered valuable insight into the European data link initiatives.

Lastly, but not least, the Pereira and Dancel families who gave their love and support in the most challenging times of my life who made me realize the value of an education.

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Chapter One - Introduction

Air Transportation's Impact on the United States Economy

The United States' gross domestic product has grown at an annual average rate of 12 percent from 1950 to 1999.[1] As the economy grew, the air transport sector's 6 percent contribution to the economy became a critical element of the United States' economy.[2] Some of the benefits of the air transport sector include inter-continental travel, businesses expansion into new geographic markets, and the affordability of leisure travel through the Airline Deregulation Act of 1978. People traveling for business or leisure who are away from home will consume goods and services to sustain their lifestyles. They'll need lodging, meals, ground transportation and tourism activities, which are major factors in stimulating the economy.[3] As travelers spend money, cities enjoy additional wealth through tax revenue, and thus are able to provide better services for residents and travelers. Furthermore, offering flight services requires a plethora of skills from the flight crew, ground crews, reservation agents, etc (see chapter two). The Air transportation industry creates these jobs and employs thousands of blue and white-collar workers. The causal relationship between the air transport industry and

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[1] "National Transportation and Economic Trends," Bureau of Transportation Statistics. Internet. February 10, 2002. Available: http://www.bts.gov/btsprod/nts/Ch3_web/3-6.htm

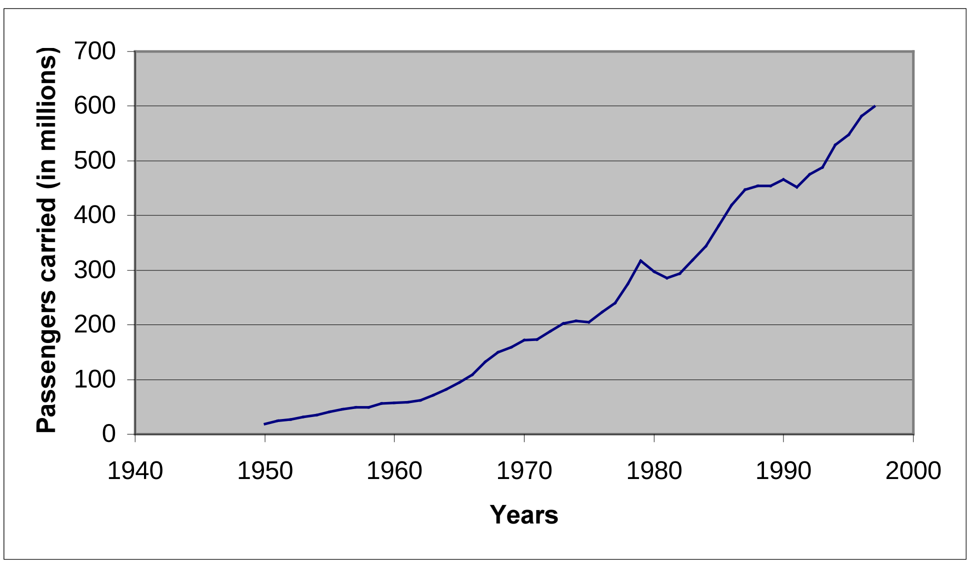
[2] "Importance of the NAS," Internet. February 12, 2002. Available: http://www.faa.gov/nasarchitecture/hilites/section1.htm

[3] http://www.eurocontrol.int/dgs/publications/en/index.html

economy is tightly coupled; any constraints on the air transportation industry impact the economy.

Air transportation was initially regulated by the Civil Aeronautics Board (CAB) who imposed barriers such as approvals to mergers, new flight routes, landing and takeoff restrictions, and most importantly inhibited startups into the market. Furthermore, due to expensive airline ticket prices, air transportation was affordable only by the wealthy and therefore not in great demand until the late 1970s (see Figure 1-1).

Figure 1-1[4] - United States Air Travel Demand 1940 - 2000



[4] Thierer, Adam. "20th Anniversary of Airline Deregulation: Cause for Celebration, Not Re-regulation." The Heritage Foundation Backgrounder. April 22, 1998. page 19.

The Boeing Company's introduction of the jet airliner into the market induced massive growth, as passengers were able to travel further distances in shorter amounts of time at lower costs.[5] In the late 1970s, the economy deteriorated as the fuel crisis overseas increased domestic fuel prices, sending the airline industry into a downward spiral. These trends exposed CAB's management inabilities to cope with the increasing dynamics of managing the airliners, prompting the federal government to deregulate the airline industry.[6]

The Airline Deregulation Act of 1978 fostered healthy competition through more flexible ticketing and pricing arrangements and the hub-and-spoke concept.[7] The hub-and-spoke concept allowed airline companies to access a greater geographic area while taking advantage of network and scale economies.[8] As a result, the cost of airline tickets drastically decreased, creating a high demand for airline travel (see Figure 1-2 for a graphical summary of the inverse relationship between price and demand).

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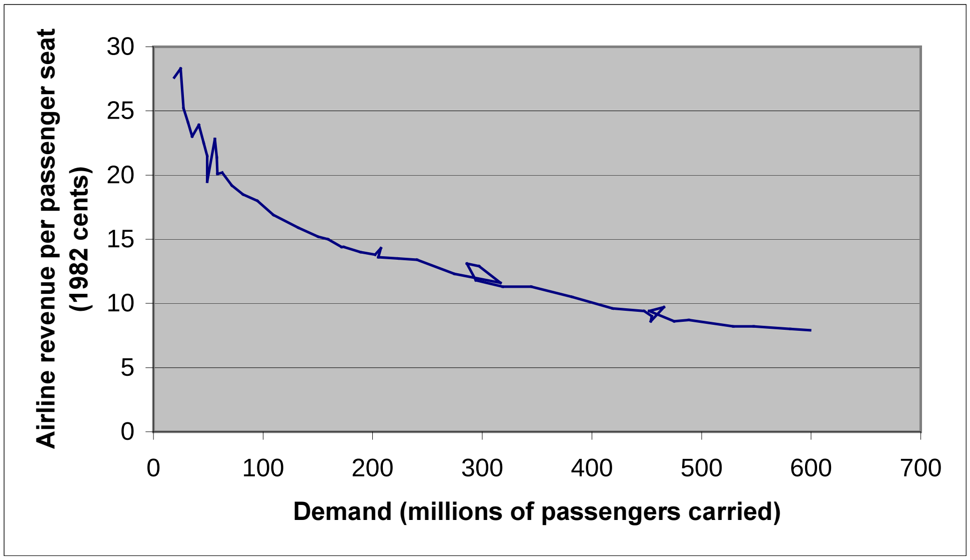
[5] "History: Jets and Rockets Take off," Internet. February 6, 2002. Available: http://www.boeing.com/companyoffices/history/boeing/747.html

[6] Thierer, Adam D. "20TH ANNIVERSARY OF AIRLINE DEREGULATION: CAUSE FOR CELEBRATION, NOT RE-REGULATION." The Heritage Foundation Backgrounder. April 22, 1998.

[7] Dempsey, Paul S., Air Transportation: Foundations for the 21st Century. Coast Aire Publications, Chandler, Arizona, 1997, page 452.

[8] Internet. Online. April 3, 2002. Available: http://www.cmis.csiro.au/or/hubLocation The hub and spoke system minimizes transportation costs across a geographic network of airports.

Figure 1-2[9] Airline Price and Demand 1940 - 2000



For example, the tourism industry created new markets as people could travel economically for leisure while businesses travelers expanded into foreign countries creating jobs and economic prosperity both abroad and at home. As markets became integrated, airline companies capitalized on the growth of air travel by offering a high frequency of flights. However, excessive flights exposed the weaknesses of the air traffic control system, which hampered the National Airspace System (NAS). [10]

Saturated communication channels at peak travel created airwave congestion problems in pilot to air traffic control communications, leading

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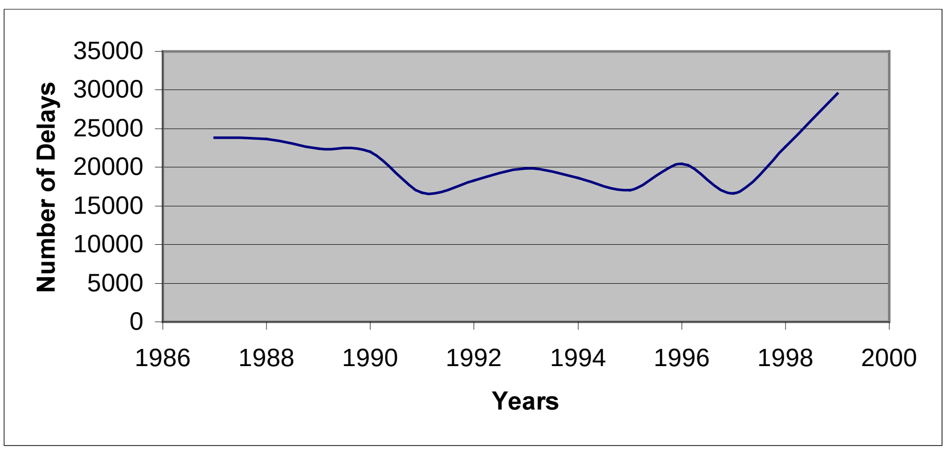
[9] Thierer, Adam D. "20TH ANNIVERSARY OF AIRLINE DEREGULATION: CAUSE FOR CELEBRATION, NOT RE-REGULATION." The Heritage Foundation Backgrounder. April 22, 1998. Page 19.
[10] "What is the National Airspace Systems?". The National Airspace system is a collection of systems, used by people, following certain procedures that provide safety and organization for aircraft flying in the sky. Online. Internet. January 20, 2002. Available: http://www.nas-architecture.faa.gov/Tutorials/NAS101.htm.

to flight delays and a rise in runway incursions.[11] Also, flight delays occurred when the pilot was unable to get in-flight advanced weather warnings affecting the en-route flight path (see Figure 1-3). These weather delays had a chain reaction on subsequent flights. Because the same aircraft would be used for multiple flight departures, a delayed flight arrival affected the next flight's departure. Hence, the net-effect was a delayed departure, which has to create a market of unsatisfied consumers.

Figure 1-3[12] Delays greater than 15 minutes caused by weather 1985- 2000



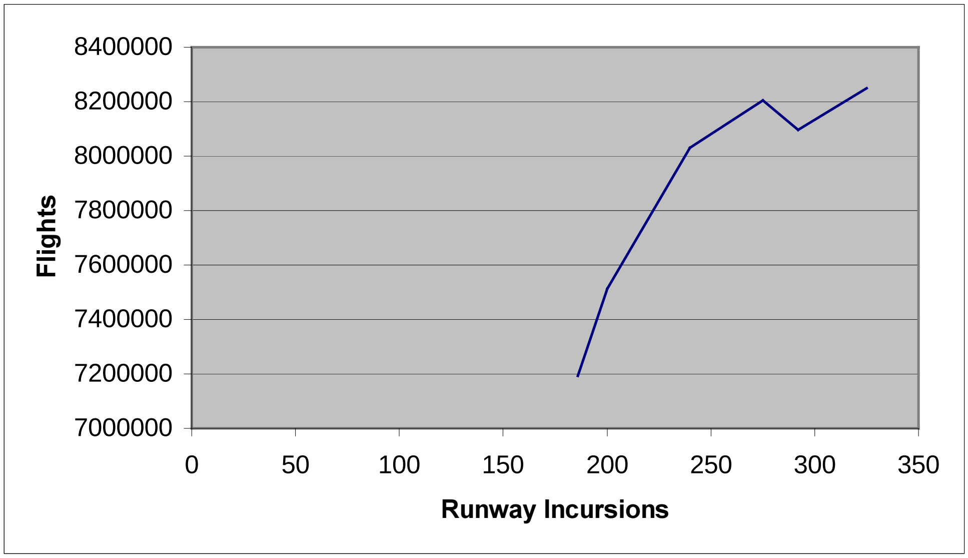
[11] Runway incursions are ground related incidents between aircraft that result in a collision due to unauthorized airport movement or the inability to correctly follow air traffic control ground movement instructions.

[12] "Table 1-58: U.S. Air Carrier Delay Greater Than 15 minutes by Cause," Bureau of Transportation Statistics, Internet. February 12, 2002. Available: http://www.bts.gov/btsprod/nts/CH1_web/1-58.html.

Secondly, runway incursion incidents increased noticeably during the 1990s, primarily due to the increase in air traffic (see Figure 1-4). It was not uncommon for pilots to wait for several minutes to get their clearances approved. During peak travel time, the single party-line channel allocated for air traffic control to pilot voice communications achieved a saturation point, as multitudes of aircraft exchanged information with air traffic controllers. Hence, to use their few precious seconds of the voice efficiently, pilots compressed their requests into highly abbreviated speech to communicate with air traffic control. Commonly, the voice channel was so busy that it restricted the pilots' ability to fully read back clearance information, which led to clearance misunderstandings and route-conformance errors.[13]

[13] Hooey, Beck L., et al. 19th Digital Avionics Systems Conference., Vo. 2, October 2000., Page 7.D.2-1. "Integrating Datalink and Cockpit Display Technologies into Current and Future Taxi Operations."

Figure 1-4[14] Runway Incursions 1993 - 1998



When the number of runway incursions and flight departures are compared in the same time frame, we can see that the number of runway incursions have nearly doubled while the number of flights has moderately increased (see Figures 1-4 and 1-5).

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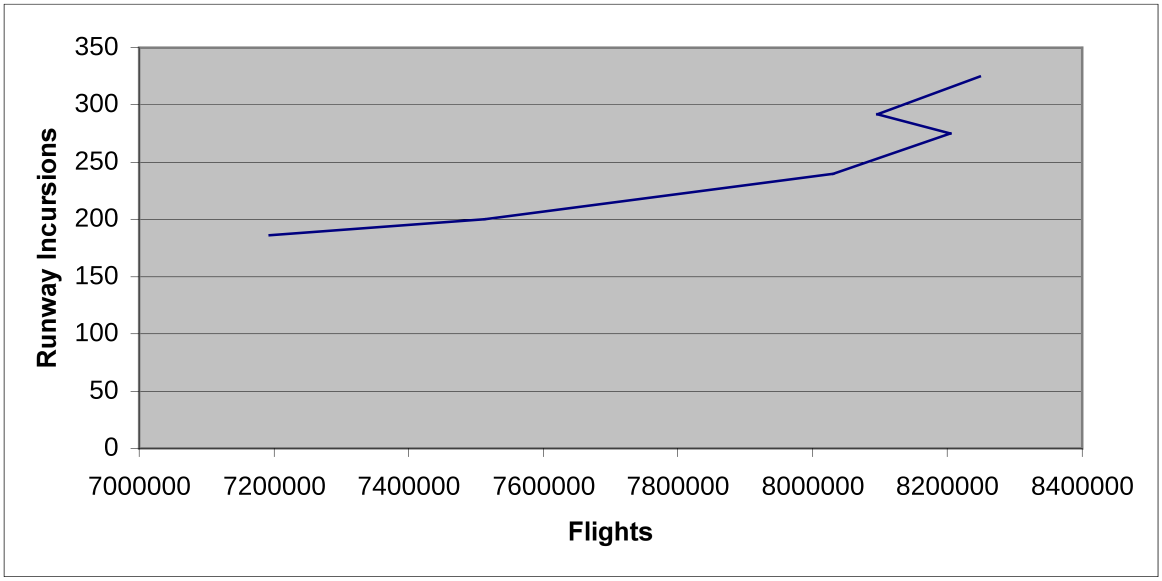
[14] Livack, Gary, James McDaniel, and Vernol Battiste. Airport Surface Moving Map Displays: OpEval-2 Evaluation Results and Future Plans. March 30, 2001. Page 2.

Figure 1-5[15,16] Runway Incursions 1993 - 1998



Airport terminal volume affecting operations delays increased from 11% in 1987 to 20 percent in 1999, an 81.8 percent increase.[17] These factors were a result of unfamiliarity at airports, low visibility, and congested communications during peak flight operations. Near mid-air collisions were a result of congested communications and the lack of airspace situational awareness as peripheral visibility was gained through air traffic control communications. Again, due to the voice channel being busy, pilots in-flight experienced difficulty contacting air traffic control

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[15] "Major U.S. Air Carrier Delays, Cancellations, and Diversions," Bureau of Transportation Statistics. Internet. March 2, 2002. Available: http://www.bts.gov/btsprod/nts/CH1_web/1-59.html. Table 1-59.

[16] Livack, Gary, James McDaniel, Vernol Battiste. "Airport Surface Moving Map Displays: OpEval-2 Evaluation Results and Future Plans." March 30, 2001. Page 2.

[17] "Table 1-58: U.S. Air Carrier Delay Greater Than 15 minutes by Cause." Bureau of Transportation Statistics. Internet. February 17, 2002. Available: http://www.bts.gov/btsprod/nts/CH1_web/1-58.html.

for an update on other aircraft in the vicinity. This dangerous predicament limited situational awareness.

Airwave congestion needs to be addressed, as it has a ripple effect on airline operations, which affects the timeliness of aircraft arrival, departure, and most importantly the productivity of leisure and business travelers. The delay of aircrafts to land or takeoff causes delays to other airlines as well as damaging the environment through unnecessary noise and air pollution.

To address congestion problems, economists advocate two broad approaches that can be categorized as supply side and demand side solutions respectively. The first approach, a supply side solution, includes an engineering approach and/or an investment in capacity (build more airports to handle congestion) while the second approach, a demand side solution, advocates an adjustment in prices to reflect the true cost of the resource.

Economics of Congestion

Engineering Solution

Because the NAS was under the jurisdiction of the air traffic control system owned and operated by the federal government, problems arose in its inability to keep up with modern technology. Consequently, the debilitated data communications link infrastructure, ACARS, compromised electronic information exchange between commercial airplane pilots and air traffic controllers.

Modern digital data link technology would relieve congestion as it is technological feasible, economically viable and has few policy implications. There are three (3) potential alternatives, VDL – mode 2, VDL – mode 3 and VDL – mode 4. By comparing, contrasting and evaluating each digital data communications link technology through a set of performance metrics, capability trade-offs, cost benefit analysis, and finally general policy issues, this thesis will prove that VDL – mode 4 is the best solution. This study hypothesizes that VDL mode 4 technology would alleviate voice congestion by providing a digital data communications infrastructure for pilot to air traffic control communications while providing a platform to build avionics systems such as graphical situational awareness applications for terminal and en-route travel.

Supply Side Solution

It could be argued that simply increasing capacity through building additional airports, runways and gates would relieve the congestion problem. There might be local community resistance to building airports such as land requirements, road access to major highways and environmental effects (noise and emissions) that would inhibit entry.[18] Once these hurdles are addressed, funding these multi-million dollar projects requires cooperation from federal and state authorities. The only concern with this proposal is the time frame; it could take decades to get governments at the federal, state and local levels to agree on a solution. Also, investment decisions should not be made unless we have the pricing right.

Demand Side Solution

If the airline ticket prices do not reflect the true scarcity of the resource, airline companies are not internalizing the social cost of their flights in terminal and en-route airspace. As a result, an airliner's internal economic cost to produce the flight service is greater than the consumer's cost for the service. In this case, the airline ticket prices should be increased to justify the true social cost for the use of the NAS, airport terminal gate and flight operations cost. However, Mayer and Sinai

[18] "Table 1-58: U.S. Air Carrier Delay Greater Than 15 minutes by Cause." Bureau of Transportation Statistics. Internet. February 17, 2002. Available: http://www.bts.gov/nts/CH1_web/1-58.html.

argue[19] that the current demand reflects the true cost of the resource and we still have a congestion problem. We therefore assume that an engineering solution is the most appropriate in the short run.

Purpose of the Study

This thesis studies digital data link communications technologies in a line-of-sight environment. Because there is much global debate over selecting the next generation VHF data link (VDL) technology, the thesis will evaluate each of them. First, we discuss which data link technology would alleviate the current data link communications congestion problem by providing reliable and effective pilot to controller communications and find the pros and cons of each of them. Secondly, an economic evaluation will be used to determine the associated costs for the air and the ground infrastructure. Lastly, an examination of the significant policy issues affecting VDL technologies will be taken under consideration. Basic knowledge of data communications and wireless communications is an aid when reading the material.

[19] Mayer, Christopher and Todd Sinai. "Network Effects, Congestion Externalities, and Air Traffic Delays: Or Why All Delays Are Not Evil," Thesis. University of Pennsylvania. Pennsylvania. October 23, 2001.

Scope of Study

In this thesis, VHF data link technologies will be evaluated for two main phases of flight: terminal and en-route. The Oceanic area, which depends on High Frequency (HF) and satellite communications via the Future Air Navigation System (FANS), will not be examined. In addition, the doppler effect will not be considered in this investigation.

Methodology and Arrangement of the Thesis

This is an analysis of different digital data link technologies in a line-of-sight environment. The discussions will be based on an introduction of the available data link technologies that are usable for this purpose. The information supporting this thesis is derived from the Interdisciplinary Telecommunications' Departments' data and wireless communications course material, relevant current journals, Federal Aviation Administration documentation and European Standards Telecommunications series documentation. In addition, information on industry trends and current issues involving the science of air traffic control was obtained at the Air Traffic Control Associations, Inc. 2001 Convention in Washington D.C. Finally, a Department of Interdisciplinary Telecommunications thesis on data links for Free Flight and several site on the World Wide Web were referenced. These resources were used to identify the best data communication characteristics such as highest data rates, greatest signal range, best signal to noise ratios, which was determined through the digital modulation scheme for each technology. In addition, those air and ground costs that providing the highest return on investment over a twenty-year life span were used in conjunction with the technical criteria to support the best technology. Furthermore, policy issues were used to qualify the barriers and promoters of the technology.

Chapter one (1) presents the introduction, methodology and structure of the thesis.

Chapter two (2) is a historical review of the purpose of data link applications, how the current system is failing to meet today's requirements and its potential contenders for replacement. The limitations of the current system are evaluated in the context of their constraint on Terminal and Enroute flight operations.

Chapter three (3) evaluates the contenders, VDL modes 2, 3 and 4, through a feasibility study, capability analysis, and performance analysis. In addition, a summary of the physical layer characteristics, multi-user communications and data link characteristics will be shown.

An evaluation of the economics of air to ground communications both for the aviation electronics (avionics) costs in cockpits and the ground-based infrastructure costs is provided in chapter four (4).

Chapter five (5) focuses on the general policy issues that inhibit and promote the advancement of aviation communications. An examination of the spectrum requirements will be performed, and a brief discussion on the major service providers will be included to investigate whether or not there is a monopoly in the market stifling technological innovation. Furthermore, an overview of the inhibitors and promoters of VDL technology within the government will be examined.

Chapter six (6) recommends a data link technology based on current technology, available economic data and policy issues.

Chapter seven (7) will examine further research that would advance the science of data link technology.

Chapter Two – Historical Background

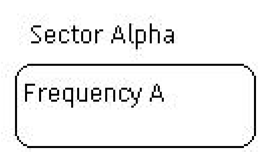
Aeronautical Radio Navigation Spectrum

Aircraft radio transceivers exchange voice or data information through the use of double sideband amplitude modulation (DSB-AM). There are 760 – 25 KHz VHF channels; two-thirds (506) are allocated for air traffic control communications while the rest are reserved for airline operational communications.

Airspace

The 506 radio channel assignments are diminishing due to a 4% annual air traffic control frequency sector growth. [20] The frequencies are being over used, which has led to demand of multiple frequencies to service sectors within a region. Figure 2-1 shows the cause of the growth from a simplified point of view.

Figure 2-1 Sector Alpha airspace using Frequency A

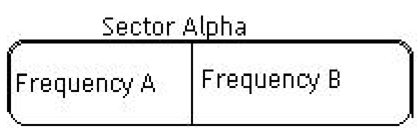


For instance, if there is only one aircraft flying through sector Alphas airspace then the air traffic controller should be able to promptly respond to the pilot's requests in a timely manner; however, when there are

[20] Wilson, J. "Airwaves congestion." Air Transport World. April 1, 2001.

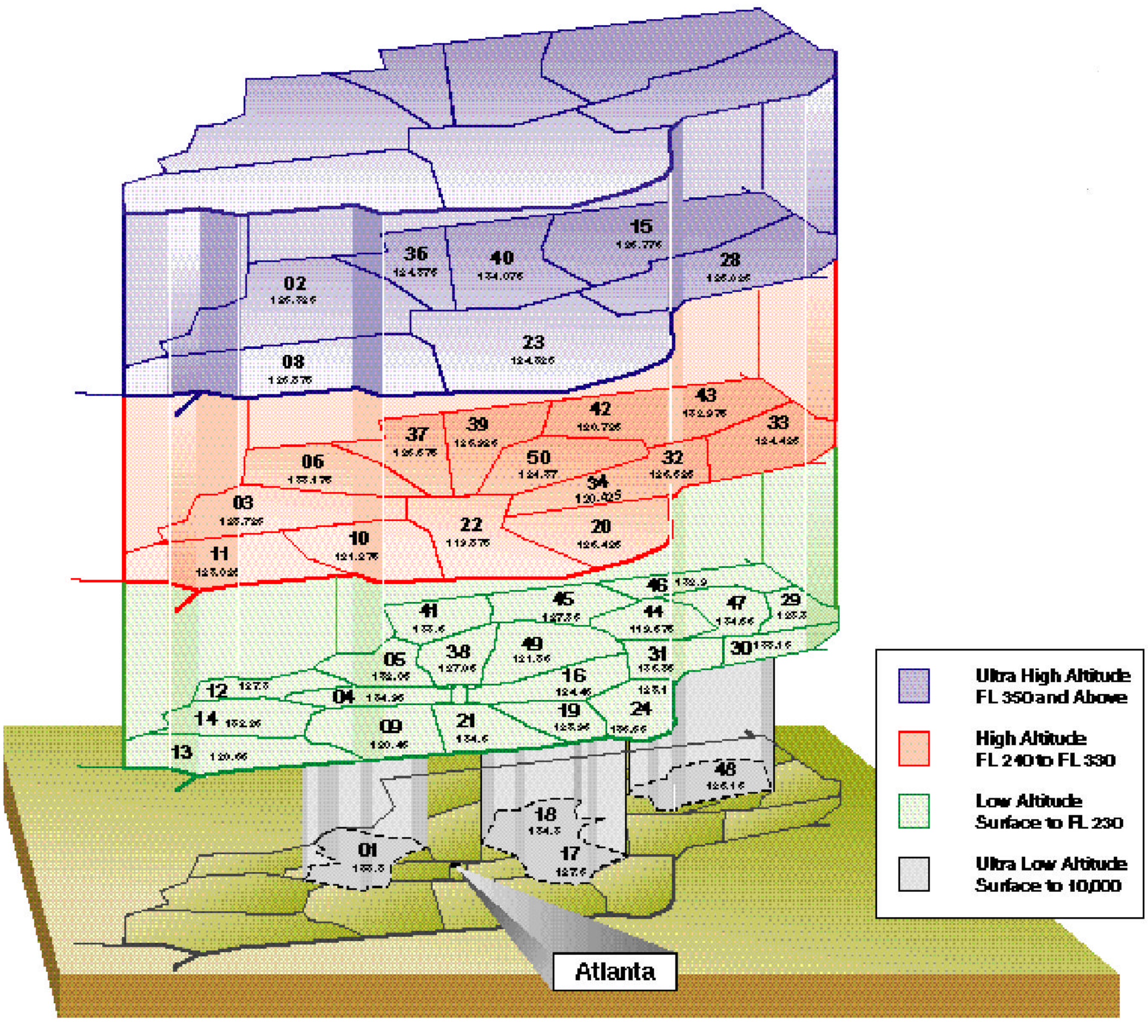
dozens of aircraft flying through sector Alpha's airspace and each is requesting flight directives, the air traffic controller may be unable to respond to each aircraft's pilot in a timely fashion leading to inadequate communications. To address this problem, another air traffic controller could be added to share the workload in Sector Alpha's airspace. Additionally, assigning an additional 25 kHz of aeronautical spectrum would be required to enable communication with the second air traffic controller. Through the division of airspace, the communications inadequacy is resolved and aircraft requests are handled in a more responsive manner (see Figure 2-2).

Figure 2-2 Sector Alpha with Frequency A and B



Again, should air traffic grow beyond the air traffic controllers ability to provide adequate communications, we can further divide sector Alpha into three (3) frequencies, if there are more frequencies available. However, the problem is that the available frequencies are diminishing. In reality, airspace is three-dimensional perspective, with flight-levels or altitudes, where several frequencies are required to provide adequate communications between air traffic controllers and pilots (see Figure 2-3).[21]

Figure 2-3 Atlanta Airspace Frequency Allocations



The gray, green, orange and blue colors represent altitudes (flight levels) ranging from the land surface to a height exceeding 35,000 feet. Each of these colors is divided into sectors that are assigned different frequencies whereby communication with ground control is enabled. For example, an aircraft in sector 13 at flight level 230 would be assigned

[21] Ball, Michael, Leandros Tassiulas, Ozur Ercetin. "Next generation satellite systems for aeronautical systems communications." University of Maryland. February 24, 1999.

frequency 132.46 for the duration of time within that sector, which could range from several minutes to several hours. Atlanta's airspace requires approximately thirty-two (32) frequencies (channels) to provide adequate air to ground communications multiply this requirement by the airspace needs of major U.S. cities and the demand exceeds the capacity of the aeronautical radio spectrum.

ACARS Infrastructure

The VHF Aircraft Communications, Addressing and Reporting System (ACARS) is an air to ground radio data system introduced in 1978 by Aeronautical Radio, Inc (ARINC).[22] The main purpose of ACARS is to provide a VHF Data Link to manage the logistical complexity of commercial flight operations through the use of the Airline Operational Control (AOC)[23], a central operations system. The ACARS infrastructure is composed of several components (see Table 2-1).

[22] Canso. "Demystifying CNS/ATM Working Group." June 1999. Page 1.2.2.1

[23] Airline Dispatch Profession. "A Brief History of the Dispatch Profession." Online. Internet. March 24, 2002. Available: http://www.dispatcher.org/history/history.html. The Airline Operational Control (AOC) was an operational control structure consisting of a system of checks and balances, which produced the highest level of safety possible for commercial airline operations.

Table 2-1 Air to Ground Communications Architecture

	ACARS Infrastructure
Applications	Airline Operational Control (AOC) Limited Air Traffic Services
Network	ACARS
Sub-Network (Air to Ground Data Communications Link)	Character Oriented Connectionless[24] Stop-n-wait protocol

The ACARS sub-network operated similarly to today's electronic mail system, transmitting 2400 bps over amplitude modulation (AM) using minimum shift keying at 25 kHz channel spacing.[25]

ACARS Applications

To ensure optimum flight management from departure to arrival, ACARS provides automated position reports of the aircraft, usually referred to as OOOIs (Out, Off, On, and In messages). OOOIs provide real-time monitoring of normal flight operations from departure to arrival. Data

[24] Roy, Aloke. "ACARS to VDL Transition Plan." Airline Electronic Engineering Consortium Data Link User Forum. January 28, 1998. Page 3.
[25] U.S. Department of Commerce. Institute for Telecommunication Sciences. "Requirements for an Air-Ground VHF Data Link for Air Traffic Control Applications." September 1974.

sensors on-board the aircraft registered "events" which are fed into an airborne computer, converted into data packets and transmitted via VHF radio to ground stations. This allows ground control computers to continuously monitor an aircraft (see Table 2-2).

Table 2-2[26] OOOI Message Example

Movement	Event	Trigger Condition	Message Contents	Example
Out	Leaving gate or parking position	Parking brake released, all doors are closed.	Out time	OUTRP 1865/31 ENZV/EKCH .SE-DNM / OUT 0650
Off	Take off	Air/ground sensor on landing gear to "airborne" state	Out time Off time Initial ETA	OFFRP 1350/28 ENGM/ENVA .OY-KKD / OUT 0859/OFF 0906/ETA 0946
On	Touch down	Air/ground sensor on landing gear to "ground" state	On time	ONRP 1499/31 ESSA/ENGM .SE-DIA / ON 0651
In	Arrival at gate or parking position	Parking brake set, any door is opened.	On time In time	INRP 0403/31 ESSA/EKCH .OY-KIL / ON 0637/IN 0643
Return-to-gate	Returns to gate after Out event	In event detected after Out event.	Return time	RTNRP 0431/31 ESGG/EKCH .LN-ROB / RTN 0522
Touch-and-go	Takes off immediately after landing	Off event detected after On event.	T&G time	TCHRP 9431/29 EKCH/EKCH .SE-DNS / TCH 1412

[26]Syrén, Björn. SAS Data link system. Online. Internet. March 1, 2002. Available: http://www.sasflightops.com/dlk/oooi.htm.

ACARS extended to Air Traffic Control Services

Over the last twenty (20) years, through a migration of Air Traffic Services (ATS) to data, ACARS was eventually extended to provide benefits to air traffic control communications. For example, ACARS applications provide pilots with in-flight weather updates at the departure and destination airports as well as at other airports along the route (see Figure 2-4).

Figure 2-4[27] METAR Weather

Aviation Routine Weather Report
K E W R   N E W A R K N J   AD RWYS 04R 22L 04L 22R 11 29 SA011200 05012KT 10SM BKN150 BKN250 18/07 A3019

Although these weather reports are abbreviated, they provide information that the pilot could use at his or her discretion to plan for landing conditions at airports. Also, air traffic control messages provide

[27] Syrén, Björn. SAS Data link system. Online. Internet. March 1, 2002. Available: http://www.sasflightops.com/dlk/weather.htm

limited text-based communications with ground control.[28] By transferring voice messages to data messages, ACARS reduces the need for a voice channel while increasing the popularity of data link communications for unspoken English. This made the language barrier transparent for foreign speaking pilots and became a widely available approved practice.[29]

ACARS Limitations

Applications

ACARS can provide a text-based exchange through a block character set that allows a maximum message of 3520 characters. As a text-based system it is constrained by both the presentation of information (via text exclusively) and the length of the message. Also, it's inherently insecure as ACARS messages are sent in clear text (not encoded) and subject to interception, which could be an inherent security risk.[30]

Sub-Network

The sub-network is composed of three major elements: physical channel, media access control layer and data link sub-layer. Because the physical channel requirements include a dedicated 25KHz channel, it can

[28] Civil Air Navigation Services Organization. "Demystifying CNS/ATM Working Group." June 1999. Page B2.1
[29] Civil Air Navigation Services Organization. "Demystifying CNS/ATM Working Group." June 1999. Page B.2.1.1
[30] Wolper, Jim. "Security risks of laptops in airline cockpits." Online. Idaho State University. Internet. March 7, 2002. Available: http://math.isu.edu:80/~wolperj

only provide data link service to one aircraft at a time, thus using spectrum inefficiently.[31] Secondly, to detect whether or not a channel is idle, the carrier sense multiple access (CSMA) protocol controls media (channel) access. Consequently, when the volume of aircraft in a sector increases, the probability of contention for the idle channel increases, resulting in a statistically higher probability of collisions. This results in a low availability of the channel as all aircraft media access attempts result in failure.

Data Link Layer

The data link layer consists of a character-based framing protocol, which delimits a frame by specifying a control character at the beginning and end of the frame (see Table 2-4).

Table 2-4 Character Oriented Frame:

SYN	SYN	STX	Header	Packet	ETX	CRC	SYN	SYN

SYN - synchronous idle

STX - start of the text

Header - header information

Packet - Data to be transmitted

ETX - End of Text

[31] Oneil, Kim. "Global Airline Operational Communications." Advanced Aviation Technology, Ltd. Online. Internet. Available: http://www.aatl.net/publications/global-AOC.htm. February 14, 2002.

CRC - Cyclic Redundancy Check

The ACARS application is severely handicapped by the stop-n-wait protocol, which limits character transmission to 220 data characters. [32] In addition, sub-network limitations such as potential security holes, physical channel capacity constraints and a poor multiple access method are exacerbated by the current patterns in air transport traffic.

The Change in Air Transport Traffic

Over the past two decades, commercial air transport traffic patterns have changed enough that the ACARS system falls short of meeting today's requirements.

First, for terminal and en-route area, a cockpit display of traffic information (CDTI) is needed to aid in situational awareness. As recently as February 1, 2002, two (2) 747s carrying 800 passengers between them came within 38 seconds of colliding over the Pacific Ocean.[33] CDTI would have provided flight crews with information about neighboring aircraft, avoiding the near catastrophe.

Secondly, a graphical display of en-route weather would allow pilots to potentially avoid turbulent weather that could compromise the safety of passengers and flight crew. In addition, this would produce cost savings by allowing optimum consumption of fuel while reducing

[32] Roy, Aloke. "ACARS to VDL Transition Plan." Airline Electronic Engineering Consortium. Data Link User Forum. January 28, 1998. Page 2.
[33] "Qantas B-747s Have Near-Miss Over Pacific," Online. Internet. http://www.flttechonline.com/news/Safety(Feb02).asp. February 2002

unnecessary weather related turbulence. Currently, air traffic controllers rely on pilots to provide crude weather updates as it affects the aircraft.

A majority of these limitations could be addressed through the use of a digital VHF data link, which would provide the necessary flexibility and scalability for future air traffic control services.

The VHF Digital Data Link

The problems associated with ACARS can be addressed using VHF Digital Data Link technology. The term VHF Digital Data Link was invented at the first meeting of the International Civil Aviation Organization (ICAO) Aeronautical Mobile Communications Panel (AMCP) in November 1991.[34] It extends the information superhighway to the world of aviation, revolutionizing the way information is exchanged and managed through digital communications.[35] A data link will provide significant benefits to users, enabling enhanced safety, operational efficiency and airspace capacity through improvements in communications and advanced communications services.[36]

There are three competing technical visions for the next generation VHF data link communications system. These data links can be classified

[34] Clinch, Philip. Director of Aircraft Operations and Navigation. SITA Aircraft Communications status report. September 2001. Page 4.
[35] "What is Data Link?" Online. Internet. Available: http://www.faa.gov/and/and300/datalink/whatis/intro.htm . October 28, 2001.
[36] Ibid.

as organized or random based on their media access[37]. Random data links determine their own transmissions schedule, disregarding current and future data link traffic. They may transmit even though other stations might be doing the same thing. On the other hand, an organized data link determines its own transmissions schedule based on some intelligent algorithm. To avoid contention, it schedules transmissions based on prior knowledge of future activities on the data link. VDL mode 2 and mode 3 are classified as random data links while VDL mode 4 is an organized data link.

VDL mode 2 promises to be a simple technical transition without the need for additional aviation electronics inside the cockpit. It provides a data rate that is ten (10) times faster than the current ACARS VHF sub network and that could meet the growing data link traffic load in the terminal and en-route areas.

VDL mode 3, or NEXCOM, a system proposed by the United States Federal Aviation Administration has the ability to transmit data, voice or a combination of both. It performs both of these functions through the use of two main multiple access protocols: Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA). The capacity of TDMA is 4 times larger than VDL Mode 2, due to its ability to transmit both voice and data in the same frame.

[37] Kjellberg, Rikard. "Capacity and Throughput using a Self Organized Time Division Multiple Access VHF Data Link in Surveillance Applications." Thesis. University of Stockholm and The Royal Institute of Technology. April 1998

VDL mode 4 was developed in Europe and utilizes Self-Organized Time Division Multiple Access (STDMA) and which is based on the TDMA protocol. This transmission medium is considered to be more than a communications solution as it can also provide surveillance information for the Cockpit Display of Traffic Information (CDTI) that could prevent runway-incursions or near mid-air collisions, provide real-time graphical weather updates as and be an aid in emergency operations for search-and-rescue missions during transponder failure.

Chapter Three - Technology

OSI Model

In this chapter we will examine the various characteristics of the three proposed data links; however, before we can explain the attributes of each data link, we will examine the fundamental data communications model, Open Systems Interconnection (OSI). The OSI model was developed by the International Organization for standardization as a computer communications architecture model for developing protocol standards (See Table 3-1).[38]

[38]Stallings, William. Data and Computer Communications. Third Edition. New York: Copyright 1991 by Macmillan Publishing Company. Page 16.

Table 3-1[39] OSI Model

	OSI	LAN examples
User interface	Application	Web browser
Transform /translate	Presentation	HTTP, FTP
Process	Session	
Data delivery	Transport	TCP
Packets	Network	IP
Frames	Data link	Ethernet, ATM
Raw bits	Physical	Twisted pair

In the radio environment the hierarchy requires different elements, particularly at the physical, data link and network layers (see Table 3-2).

[39] "VDL 4 radio design." Radio Link Design. Sectra Corporation. Toulouse, France. June, 2000.

Table 3-2 OSI Model referenced with VDL Technology

	OSI	VDL mode 2, 3 or 4
User Interface	Application	CDTI, Cockpit Display of Weather, CPDLC
Translate	Presentation	Data Link Service
Process	Session	Data Link Service
Data Delivery	Transport	Data Link Service
Packets	Network	Data Link Service
Frames	Data Link	CSMA, TDMA, STDMA
Raw Bits	Physical Layer	VHF Channel

Physical Layer

This layer provides transmission over a VHF Radio Frequency channel. It deals with the mechanical, electrical, functional, and procedural characteristics to access the physical medium.

Data Link Layer

This layer sends blocks of data, also known as frames, across the VHF channel with the necessary error control, flow control and synchronization. By design, VDL modes 2, 3 or 4 use CSMA, TDMA and STDMA to provide multiple access to a channel. Although the Code Division Multiple Access (CDMA) scheme shares many of the same properties as STDMA, it is not addressed as a solution primarily because this investigation deals with VDL technologies existing in industry.

Network Layer

The network layer is responsible for establishing, maintaining and terminating connections. As an aircraft travels from one geographic region to another, it will need to switch from one ground station to another, establishing and terminating connections frequently.

VDL – mode 2 detailed analysis

- *Radio Frequency Physical Characteristics*
    - Requires 25 kHz of spectrum to provide service
    - Required signal to noise ratio
        - 26 to 27 dB[40]
    - Number of guard band frequencies:
        - Two (2) guard bands
- *Protocol Physical Layer Characteristics – OSI Layer 1*
    - Frequency Modulated Differential Eight-Phase Shift Key (D8PSK)
    - Data rate
        - simplex 31,500 bits per second per 25 kHz channel
        - 10,500 symbols per second
- *Data Link Layer – OSI Layer 2*
    - Media Access Control (MAC) – Carrier Sense Multiple Access (CSMA) protocol to control access to between the aircraft and the ground station. (Slotted Aloha)
    - Data Link Sub Layer
        - Go-back-N connection-oriented with packet sizes up to \ 2048 octets.[41]

[40] "VDL 4 radio design." Radio Link Design. Sectra Corporation. Toulouse, France. June, 2000.
[41] Roy, Aloke. "ACARS to VDL Transition Plan." Airline Electronics Engineering Consortium Data Link User Forum. January 28, 1998, Page 5.

- Bit – oriented yields a 10 times greater transmission capability than ACARS[42]
    - Fixed length packet
    - Segmentation is possible. [43]

Feasibility Analysis

In January 2002, the Miami Air Route Traffic Control Center began a pilot program using VDL mode 2 for Controller Pilot Data Link Communications (CPDLC), a data link application.[44] CPDLC build I goals were to provide transfer of voice communication, initial contact, altimeter setting and limited text-based communications among pilots and air traffic controllers proving the operational feasibility of the data link technology.[45]

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[42] "Migration to VDL – mode 2." C/AFT Datalink Sublayer group. Online. Internet. March 12, 1998. Available: http://www.boeing.com/commercial/caft/reference/meetings/98_03_12/Vaughn.pdf. Page 5.
[43] Roy, Aloke. "ACARS to VDL Transition Plan." Airline Electronic Engineering Consortium Data Link User Forum. January 28, 1998, page 5.
[44] Personal Interview. Darby, Evan. Federal Aviation Administration. William J. Hughes Technical Center. February 2002.
[45] Murphy, Michael. "Air/Ground ATN Implementation Status Seminar." ATN Systems, Inc. Online. Internet. December 2001. Available: http://www.icao.int/icao/en/ro/apac/atn/SP23.pdf

VDL – mode 3 detailed analysis

- *Radio Frequency Physical Layer Characteristics*
    - Requires 25 kHz of spectrum to per channel
    - Required signal to noise ratio
        - 26 dB
    - Number of guard band frequencies:
        - Two (2)
- *Protocol Physical Layer Characteristics – OSI Layer 1*
    - Frequency Modulated Differential Eight Phase Shift Key (D8PSK)
    - Data rate
        - simplex burst rate is 16,500 bps per 25 KHz channel
        - 16,500 symbols per second
    - Voice rate
        - 19,200 bps per 25 KHz channel
- *Data Link Layer – OSI Layer 2*
    - Media Access Control (MAC)
        - Carrier Sense Multiple Access (CSMA) protocol to control *data communications* access between the aircraft and the ground station.

- Time Division Multiple Access (TDMA) protocol to control *voice and data communications* access between the aircraft and the ground station.

- Data Link Sub Layer
  - Bit – oriented
  - Fixed length data packets

Feasibility Analysis

VDL mode 3 has been simulated in a variety of conditions and there is support for this particular data link by the U.S. government.[46] In addition, ITT industries, a radio manufacturer was recently awarded a multi-million dollar contract to supply ground radios throughout the U.S. Despite the lack of operational field tests, the FAA is promoting this technology to eventually succeed VDL – mode 2.

[46] MITRE. "VHF Digital Link/ TDMA Radio Prototype Overview." VHF Data Link Team. September 1995.

VDL – mode 4 detailed analysis

- *Radio Frequency Physical Layer Characteristics*
    - Requires 25 KHz of spectrum to per channel
    - Required signal to noise ratio
        - 10 dB
    - Number of guard band frequencies:
        - 0
- *Protocol Physical Layer Characteristics – OSI Layer 1*
- Frequency Modulated Gaussian Frequency Shift Keying (GFSK)
- Data rate
    - simplex data rate 19,200 bits per second per 25 KHz channel
    - 10,500 symbols per second
- *Data Link Layer – OSI Layer 2*
    - Media Access Control (MAC) – Synchronized Time Division Multiple Access (TDMA) protocol to control access between the aircraft and the ground-station. The system divides the communication channel into time-slots that can each be used by a radio transponder mounted on the aircraft or a ground station for data transmissions.

- Data Link Sub Layer
    - Ability to provide quality of service
    - Bit –oriented
    - Flexible length data packets
    - Segmentation is possible.[47]

Feasibility Analysis

The North European ADS-B Network (NEAN) pilot program was completed in mid-1998 with cooperation from several countries and commercial airliners. Through a variety of operational tests that also included mobile VDL-mode 4 equipped vehicles, the VDL mode 4 data link system was validated.[48]

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[47] Roy, Aloke. "ACARS to VDL Transition Plan." Airline Electronic Engineering Consortium Data Link User Forum. January 28, 1998, page 5.
[48] Nilsson, Johnny. Director of the Swedish Civil Aviation Administration. "Short Presentation of VDL Mode 4 and some European projects."

VDL modes 2, 3 and 4 comparison tables

Table 3-3 Physical Characteristics [49,50,51]

	Voice	Data	Spectrum Required	Signal to Noise Requirement	Guard Channel Requirement
VDL – mode 2	No	Yes	25 KHz	26 to 27 dB	2
VDL – mode 3	Yes	Yes	25 KHz	26 to 27 dB	2
VDL – mode 4	No	Yes	25 KHz	10 dB	0

Table 3-4 Data Communication Characteristics I

	Data rate	Frequency Modulated Digital Modulation	Communications Sub-network	Network Control
VDL – mode 2	31.5 Kbps	D8PSK	Air to Ground	Ground Controlled. No Timing required
VDL – mode 3	31.5 Kbps	D8PSK	Air to Ground	Ground Controlled. Ground Timing.
VDL – mode 4	19.2 Kbps	GFSK	Air to Ground, Air to Air	Ground or Air Controlled. Ground or Air Timing

[49] Oneil, Kim. Online. Internet. February 19, 2002. Available: http://www.aatl.com/datalinkoptions.htm

[50] "Standards and VDL Standards and recommended practices." Online. Internet. February 29, 2002. Available: http://www.eurocontrol.int/fvhf/Deliverables/WP5000/Standards_andVDL_SARPs.zip

[51] Lans, Hokan. Personal Interview. VDL mode 4 Inventor. March 12, 2002.

Table 3-5 Data Communication Characteristics II

	Multiple Access Classification Data only	Communication connections per channel
VDL – mode 2	Random (CSMA)	Limited to 1
VDL – mode 3	Random (CSMA)	Limited to 4 3 voice/ 1 data = 4 2 Voice/ 2 data = 4
VDL – mode 4	Organized (STDMA)	Scaleable

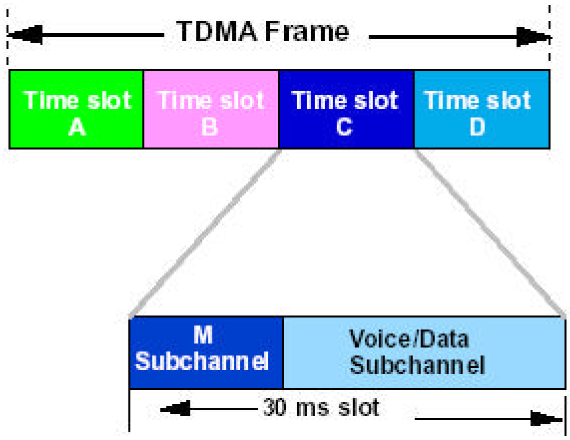
Capabilities Analysis for VDL modes 2, 3 and 4

These competing digital communication technologies all offer data link communications, but there are important differences among them. Using Tables 3-3, 3-4, and 3-5, we'll compare and contrast VDL mode 2, 3 and 4.

VDL MODE 3

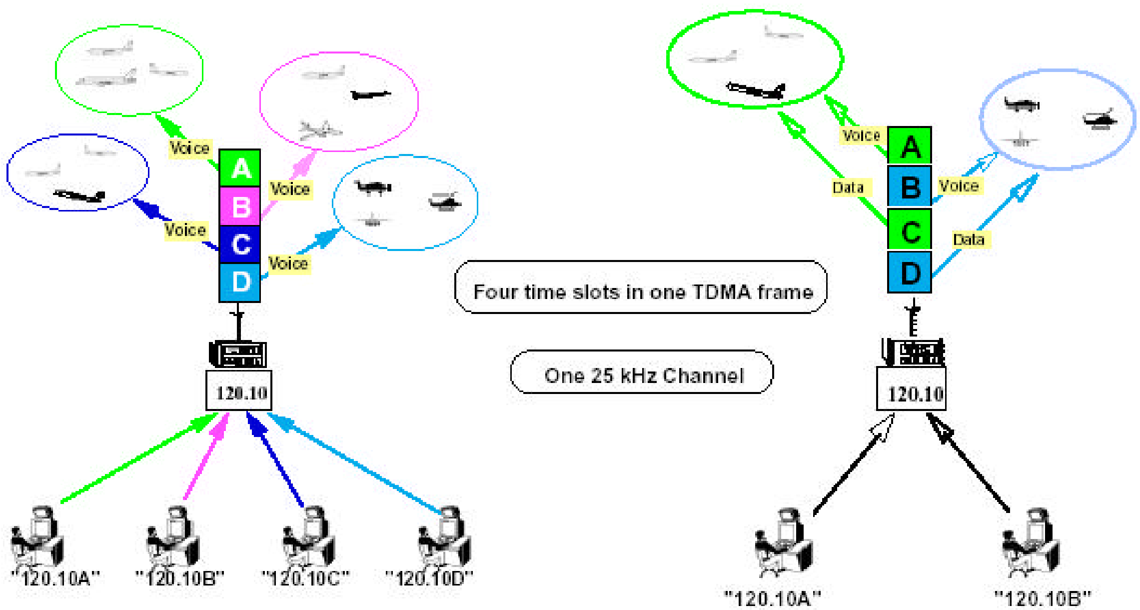
First, voice and data are available in VDL mode 3, but unavailable in modes 2 and 4. This makes VDL mode 3 a multi-purpose technology as it shares a single 25 kHz channel for voice and data simultaneously. It achieves this with the TDMA frame structure consisting of a slot length and a frame period (see Figure 3-1).

Figure 3-1 TDMA Frame



There are a variety of configurations that allow data and voice to be transmitted simultaneously (see Figure 3-2).

Figure 3-2 TDMA Communications Model



The primary purpose of the technology is to transmit digital voice and data. This assignment is controlled from the ground station and cannot be changed dynamically. The Air traffic environment is a highly dynamic one, constantly changing due to elements such as weather conditions, airspace traffic, congested communication channels, etc. VDL mode 3's inability to adapt makes it a poor application in this environment. In addition, inherent design limitations such as the modulation scheme, guard channel requirement and media access contribute to its shortcomings. First, the D8PSK digital modulation scheme is sensitive to interference, fading and shadowing conditions as well as linear and non-linear distortions. Its high signal to noise power requirement, 22dB, requires two (2) guard band channels to protect adjacent channels from the interference. This implies three (3) channels (frequencies) are required to service a single aircraft, which reduces the number of frequencies available in the airspace, reducing the services available to other aircraft.

If data is transmitted in all four (4) time-slots, the random access mode, CSMA, is used to control access to the media. This random mode behaves similarly to the Aloha algorithm. Although VDL mode 3 attempts to provide digital voice and data simultaneously its design flaws overburden the aeronautical radio navigation spectrum while its modulation scheme makes it unreliable for communications in dense airspace traffic.

VDL Mode 2

VDL mode 2 provides only a data link service to aircraft and shares some of the characteristics of VDL mode 3. For example, the digital modulation scheme is the same, which contributes to its failures. Due to its sensitivity to noise, two (2) guard channels are required to protect the fundamental signal from noise. That means three (3) frequencies are required to service a single aircraft, which is unnecessary overhead as aeronautical radio frequencies are in short supply (see chapter two). In addition, VDL mode 2's media access is based on the Aloha algorithm, which operates like Ethernet protocol in a ground network. Consequently, an increase in packet traffic results in an increase in access delay making this protocol unsuitable for time-critical data.[52]

VDL Mode 4

VDL mode 4 has many inherent advantages over its competitors, VDL modes 2 and 3. First, it transmits the FM signal with a Gaussian Frequency Shift Keying (GFSK) modulation scheme, which is much more power efficient than D8PSK, resulting in lower interference. This increases the frequency re-use factor and ultimately increases the

[52] Oneil, Kim. "Datalinks sorting fact from fiction." Online. Internet. January 23, 2002. February 2, 2002. Available: http://www.aatl.net/publications/datalinkoptions.htm. Page 9.

airspace capacity. Also, access to the media is time-multiplexed through a self-organization scheme with a data rate of 19,200 bits per second. Secondly, it is based on a cellular technology that requires a low signal-to-noise (S/N) ratio increasing the frequency re-use factor and thereby allowing an increase in capacity. Thirdly, built in redundancy enables operation without the use of a ground station for timing information. This dynamic feature is especially useful when ground stations are unavailable in rural areas or when they fail. VDL mode 4's adaptability automatically establishes air-to-air communications with neighboring aircraft and obtains timing information through the use of the Global Navigation Satellite Systems (GNSS) receiver such as a Global Positioning System (GPS).[53] An aircraft equipped with this technology continuously receives its own position, from the position sensor, and then repeatedly broadcasts it on a VHF data link any where in the world.[54] This is commonly known as the Automatic Dependent Surveillance Broadcast (ADS-B) and could be very useful in locating aircraft when transponders fail or are manually disengaged.

In conclusion, VDL mode 4 should be chosen as it fulfills the requirements for current and future communications demand while providing a platform for surveillance applications.

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[53] Oneil, Kim. "Datalinks sorting fact from fiction." Online. Internet. January 23, 2002. February 2, 2002. Available: http:///www.aatl.net/publications/datalinkoptions.htm. Page 9.
[54] Kjellberg, Rikard. "Capacity and Throughput using a Self Organized Time Division Multiple Access VHF Data Link in Surveillance Applications." Thesis. University of Stockholm and The Royal Institute of Technology. April 1998

Chapter Four - Economics

The benefits of VDL technology impact two major areas, Air Traffic Services and Airline Operational Communications. Air Traffic Services is considered to be a highly critical area for the safety of flight operations while Airline Operational Communications is classified as a secondary area that could leverage the derived benefits. In the following two sections, the costs and benefits of VDL technology will be discussed for of the major areas in turn.

Air Traffic Services

VDL technology requires specialized radio equipment for the aircraft and ground stations of Air Traffic Services. Upgrading 37,000 ground stations with digital radio equipment would be an enormous economic burden for private industry, as the costs and resources required to undertake such a project are enormous. However, air traffic control remains under the jurisdiction of the federal government, specifically the FAA, which handles these projects. In the simplest form, the ground VDL technology equipment consists of a digital radio transmitter and receiver (transceiver), an antenna and computer software, while the air equipment includes new aviation electronics to provide a platform for advanced application systems. Estimated startup costs of the various VDL technology modes for one ground station are shown in Table 4-1.

Table 4-1 Estimated Ground Base Station Costs[55, 56, 57]

Technology	*Digital Radio Transceiver, Antenna*	*Yearly Site Lease*	*Yearly Maintenance*
VDL mode 2	$30,000	$3800	$500-$5,000
VDL mode 3	Unknown	$3800	Unknown
VDL mode 4	$87,420	$3800	$8742

Many people in the industry were unable to address the exact cost of a VDL mode 3 radios, but there are competitive estimates ranging from $25,000 dollars to $30,000 dollars. More importantly, through volume sales, the cost of the ground based radios would decrease and thus is not a major economics factor in determining air to ground infrastructure costs.

On the other hand, the airborne infrastructure faces numerous obstacles ranging from avionics equipment costs (see Table 4-2) to grounding revenue aircraft for a specific time period to upgrade existing aircraft avionics.

[55] Demers, Dennis. Personal Interview. SITA. March 15, 2002
[56] Dell'Orto, Luca. Eurocontrol. Personal Interview. March 15, 2002.
[57] Eurocontrol. Online. Internet. March 2, 2002. Available: http://www.eurocontrol.be/ads/deliverables/01/stage1/cba_v4.pdf Page 169

Table 4-2 Estimated Equipment Costs Per Aircraft [58, 59, 60]

Technology	*New Aircraft*	*Existing Aircraft (Analog Avionics)*	*Existing Aircraft (Digital Avionics)*	*Hourly Labor Costs*
VDL mode 2	$77,900	$110,800	$46,000	$70
VDL mode 3	$64,500	$256,300	$116,400	$70
VDL mode 4	$49,392	$110,580	$61,000	$70

The avionics for new aircraft is not prohibitive; it's the retrofitting of existing aircraft that is the most expensive. Airliners have to consider not only the equipment costs, but also the opportunity cost of down time associated with having an aircraft out of revenue service. Acquisition of new avionics into an airline's fleet can take several years and it is not unusual for the cost of removing the aircraft from service for a retrofit to exceed the purchase cost of the avionics. Therefore airlines plan major changes in avionics and communications equipment to coincide with regularly scheduled aircraft maintenance cycles.[61] As Euro-control has shown, the aircraft equipment costs are far greater than the ground costs, placing the economic burden squarely on the airliners. [62] To ease this burden and provide immediate benefits, incentives such as preferential

[58] Nickum, Kames D. MITRE Technical Report. "Air Transport Avionics Cost Estimation Related to Future Communication Transitions: Coordination Draft." April 2000. Page 28.
[59] Narkuss-Kramer. Marc and John Gonda. "Aviation Communications: The Difficult in finding a future direction and what needs to be done. " 20th Digital Avionics Systems Conference Proceedings. Volume 2. October 2001
[60] http://www.eurocontrol.be/ads/deliverables/01/stage1/cba_v4.pdf
[61] Report on FAA's progress and Plans for Implementing Data Link for Controllers and Pilots. Online. Internet. November 22, 2002. Available: http://www.cena.dgac.fr/~sagnier/datalink/audit_faa_dl.htm#titre15.
[62] Dell'Orto, Luca. Personal Interview. Eurocontrol. March 15, 2002.

flight routes, departure slots, etc. are being proposed by the air transportation industry. These public policy initiatives could create attractive economic benefits to pioneer airliners while promoting the proliferation of VDL technology.

The public, not the airline investors, would be subsidizing the majority of the economic costs through taxpayers' dollars, as the social benefits outweigh the costs. These social benefits or spillover effects discussed in chapter one and include benefits to society through integrated product and labor markets, which increase productivity, trade, tourism and employment. The air transport industry can either provide prosperous economic growth or adversely impact it through a reduction in tourism, business travel and blue and white-collar jobs, as is currently the case since September 11, 2001.

Although the FAA is advocating VDL mode 2, it does not necessarily have the most beneficial return on investment (see Figure 4-1). VDL mode 2 is considered to be an intermediate solution and is not scaleable for promulgating data link applications beyond CPDLC, which allow voice messages to be transferred to data messages. In 2010, VDL mode 3 is expected to become operational and eventually replace VDL mode 2.[63] Therefore, it is easier to evaluate the benefits of VDL modes 2, 3 and 4 over a long-term life span (see Figure 4-2).

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[63] "Secretariat responds to ICAO ELT Proposals." Online. Internet. September 1998. Available: http://www.iaopa.org/info/worldfax/worldfax0998.html

Figure 4-1 VDL Categorizations

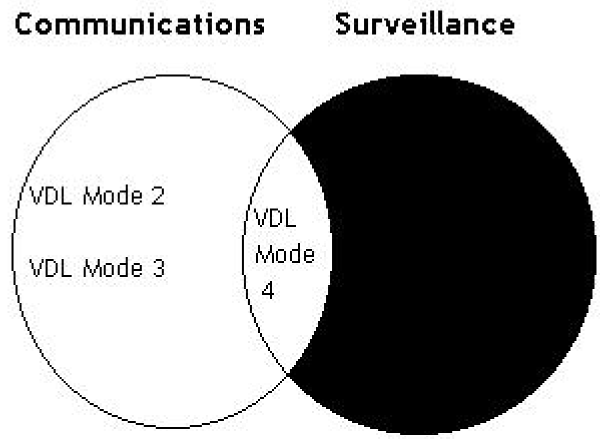

Figure 4-2 VDL Technology Time Line

2002...2010...2022

I(1), C(1)   B(1) . . . B(1)j
VDL Mode 2 -----------------------→| (End of Life)
$C_{o,vdlm2}$ = - C1 C(1) . . . C(1)j

I(2), C(2)   B(2) . . . B(2)j
VDL mode 3 ---------------------------→
$C_{o,vdlm3}$ = - C2   C(2) . . . C(2)j

I(3), C(3)   B(3)   .   .   .   B(3)j
VDL Mode 4 --→
$C_{o,vdlm4}$ = - C3   C(3)   .   .   .   C(3)j

KEY

C = Cost (Maintenance, Operational)
B = Benefit
I = Initial Investment Cost (Infrastructure)
I > C
VDLM2 = VDL mode 2
VDLM3 = VDL mode 3
VDLM4 = VDL mode 4

Assumptions

20 year life span
B3 > B1 > B2
R = discount rate

Discount rate is the same for VDL modes 2, 3 and 4 as the investment costs are assumed to be uniform.

The assumptions provide some context to evaluate each VDL technology ranging from product life to associated risk for each VDL technology. Based on ACARS life span exceeding twenty years, next generation technology should be expected to last at least this long.

First, VDL mode 2 can expect to achieve an end of life in the year 2010 while VDL mode 3 becomes its successor. Second, there are additional economic costs associated with a transition that would need to be taken under consideration. Lastly, initial investment costs for VDL mode 2 and VDL mode 3 are not prohibitive, but the transition costs from VDL mode 2 to VDL mode 3 are unknown (see Table 4-3).

Table 4-3 Estimated Net Benefits

VDL Mode 2 cost = - I(1) - C(1) + B(1)
VDL Mode 3 cost = VDL mode 2 costs - I(2) - C(2) + B(2)
VDL Mode 4 cost = -I(3) - C(3) + B(3)

This would be a risky economic venture for those airliners committed to VDL mode 2 who may not be willing to upgrade their fleets again as VDL mode 3's initial investment costs coupled with maintenance and operational costs over the life of technology could outweigh its benefits. This would undermine the rationale for VDL mode 3 leaving VDL mode 4, as the only logical competitor.

For further cost benefit analysis, consider that the recurring costs for each technology, C(1) = C(2) = C(3), approaches zero. Next, discount to the present value the investment costs of VDL modes 2 and 3, I(2) and I(3), respectively. If the summation of I(2) and I(3) is equal to or greater than VDL mode 4's investment cost, I(4), then it is more economical to invest in VDL mode 4. Therefore, VDL mode 4 is ultimately a much more cost-effective solution than its competitors as it lends itself to communication and surveillance applications (see Table 4-4).

Table 4-4 Application and Data Link technology requirement

APPLICATION	DESCRIPTION	TECHNOLOGY REQUIREMENT
Communications Controller-Pilot Data Link Communications (CPDLC)	Pilot to air traffic control communications through the use of data messages.	VDL mode 2 VDL mode 3 VDL mode 4
Communications Graphic Weather Service	Graphical color weather displays for monitoring en-route weather.	VDL mode 2 VDL mode 4
Surveillance Search-n-rescue	Provides the last known position of an aircraft.	VDL mode 4
Surveillance Cockpit Display of Traffic Information (CDTI)	Pilot Situational Awareness in terminal/enroute airspace and on the ground.	VDL mode 4

Airline Operational Communications

Though VDL 4 technology is primarily geared toward highly critical air traffic systems, it could be extended to other facets of flight operations such as airline operational communications (see chapter two) to provide enhanced services.[64] It's conceivable that with an on-board desktop terminal, security interface to control access, printer and a data link to an airline operations center, flight attendants could issue passenger boarding passes for connecting flights. This service could be used in the event of a delayed arrival at the destination, saving the passengers time and hassle.

Today pilots carry flight bags that contain a number of effects required for flight planning. One of these items is a chart created by Jeppesen Sanderson, Inc., a subsidiary of The Boeing Company. Among other things, these manuals highlight airspace classifications, military airspace, runway alignments, and air traffic control frequencies within the terminal area. Normally these manuals have an expiration date, as information such as new air traffic control frequencies, airport construction warnings, etc. is updated. Consequently, it is a time-consuming and expensive process for Jeppesen Sanderson, Inc. to constantly keep abreast of these updates that must be accurately published to ensure the safety of flight operations. Furthermore, high production costs incurred from publishing these manuals are passed on to the consumer, the pilot. It's conceivable that this process could be streamlined through a data uplink directly into the cockpit via avionics, increasing the effectiveness of their core business while passing on the economic savings to both the producer and consumer of these charts.

[64] "VDL Mode 4 is more than being just the optimal ADS-B datalink." Online. Internet. January 21, 2002. Available: http://www.transpondertech.se/node1583.asp

Also, flight data recorders could be programmed to automatically transmit data link information when transponders are manually disengaged or the emergency squawking code is engaged. Critical aircraft information such as location, flight number, voice or data information could be transmitted to the ground station. This information could save precious time by automatically notifying the appropriate federal agencies and alerting the military via the North American Aerospace Defense Command, which monitors unusual airspace activity over the U.S. and Canada. In the event of a catastrophe, where an aircraft crashes, significant lead-time could be used to determine the cause of the accident for unusual aircraft defects while authorities examine the crash area for the "black boxes" and physical evidence. Furthermore, airline operations communications could be extended to maintenance staff that accesses the cockpit to obtain the optical disks, which have data on the general welfare of the aircraft. Quality assurance information such as engine performance, structural integrity, hydraulic pressures, oil levels, etc are recorded on these optical disks and used for maintenance scheduling. Automatic transmission of maintenance data could provide ground crews with advance warnings to prepare for the flights arrival at the terminal gate. This would save time on the ground while flight routing, passenger manifests and detailed taxi instructions could expedite departures. These benefits would improve the overall effectiveness and efficiency of the ground operations team.

In conclusion, based on a high-level cost benefit analysis among VDL modes 2, 3 and 4, VDL mode 4's economic costs are straightforward. They include initial investment costs and subsequent maintenance costs while VDL modes 2 costs outweigh its benefits due to its inability to scale beyond the next decade. Finally, VDL mode 3's costs are much more riskier as the transition cost from VDL mode 2 is largely unknown. Therefore, VDL mode 4 simplicity in design offers the best economic investment.

Chapter Five – Public Policy

The Federal Communications Commission (FCC) is responsible for the radio spectrum within the United States. It is a valuable commodity shared by three main entities: the public, the private and the military. Without spectrum, wireless devices such as radios have no media to send or receive information. Therefore, the FCC has allocated the VHF 117.975 - 137 MHz for civilian aircraft to use for communications with air traffic controllers. [65]

VDL Modes 2, 3 and 4 Spectrum Usage

VDL modes 2, 3 and 4 all fit within the existing aeronautical radio navigation spectrum without interfering with current DS-AM aircraft while remaining compatible with the 25 kHz spacing requirements. Co-existence is vital for VDL technology as it should not displace existing services (analog radio communications), as the transition from analog to digital data communications is likely be time intensive. [66] The efficiency and capacity of each data link should be closely examined for adaptability to future flight operational requirements such as long-term data-link, Free Flight and airline operational communications initiatives that are widely discussed today.

Inhibitors of VDL Technology

Air traffic control regulation

Since the Airline Deregulation Act of 1978, the federal government's regulatory roles have included the establishment and the

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[65] Military & Aerospace Electronics. "U.S. and European aviation authorities struggle with dwindling communications bandwidth" July, 2001. http://library.northernlight.com/PB20011121040002271.html?lnid=ei4hOnhjbz4LcARsfGoIXgFWWkgHHRNAcwx5FQA%3D&cbx=0#doc

[66] Oneil, Kim. Advanced Aviation Technology, Ltd. Online. Internet. January, 2002. Available: http://www.aatl.net/publications/datalinkoptions.htm

enforcement of safety standards as well as the management of the air traffic control system.[67] Today, two decades later, there is a growing consensus that the air traffic control system is primarily a high technology service business aimed at providing commercial airline service, 24 hours a day, 7 days a week.

Millions of taxpayers' dollars have been consumed in feasibility studies with much focus on VDL mode 2 and 3 while VDL mode 4 has not been given the attention it deserves. Furthermore, air traffic control towers rely on much the same technology they used during its inception decades ago. This antiquated technology coupled with steady increases in air traffic over the past three (3) decades has led to an increase in runway incursions, airspace and airwave congestion.

Airline Communication Services Monopoly

In order for aircraft to remain in contact with the air traffic control on the ground through out the duration of a flight, it relies on a human computer interface via avionics. These avionics are usually pre-programmed by the respective manufacturers to connect with the ground network through the dominant service provider, ARINC who owns 90% of the U.S. market while its competitor SITA owns 10%[68] [69] Because there

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[67] Thierer, Adam. "20th Anniversary of Airline Deregulation: Cause for celebration, not re-regulation." The Heritage Foundation Backgrounder. April 22, 1998. Page 5.
[68] Zorn, Linda. Personal Interview. ARINC Marketing. March 28, 2002.
[69] Warnock, Mark. Personal Interview. Senior Sales Manager. SITA. March 28, 2002.

are two service-providers, could it be cumbersome for new competitors to provide services in this niche market?

New competitors would find the barriers to entry include the high costs associated with the ground infrastructure as well as the unusually close involvement with regulatory agencies such as the FAA. With these barriers, some private industries would come to a realization that their innovative telecommunication products need government approval, FAA certification, before being incorporated in to the air traffic control system. These certification processes are required to ensure the interface to new systems are not compromised through the addition of modern technology, hence a rigorous operational testing process enforces these requirements. This certification process is time-intensive consuming vast amounts of money and resources that could reduce profit margins, a practice, that most private industries would rather not risk.

On the other hand those industries already established in the air to ground communications fields, anticipate significant benefits. For instance, from a business perspective, it is in the best interests of the radio manufacturers and service providers to produce the goods and services requested by their client, the FAA, even though the solution may adversely impact future air traffic services initiatives. The relationship among the three stakeholders could be heavily influenced by the quest for lucrative contracts rather than for addressing a crippling air traffic control system.

Despite U.S. advocacy for VDL mode 2, the Europeans continue to run operational tests with VDL mode 4 because they are not yet convinced that VDL mode 2 or 3 is the best technology solution (see chapter three). Unfortunately, the fate of VDL technology is as much a politicized process as it is a technological and economic valuation.

Promoters of VDL Technology

Incentives for airlines

Most commercial airlines want to see a return on their investment before upgrading new avionics; however, it is widely acknowledged that major benefits will be generated when 80 percent of the fleet is equipped. [70]

As a result, to urge airliners to act as pioneers incentives are proposed through preferential air routes, terminal departure slots at airports.[71] As mentioned in chapter one, the social benefits of the air transport industry are not trivial. Air transportation impacts a variety of industries such as tourism, business globalization and employment. When air transport adversely impacts the economy, these industries suffer the social costs through unemployment, reduced business and leisure travel. Through public investments, many of these social costs can be deterred through passenger ticket taxes to help airlines equip their cockpits with modern avionics technology.

[70] Air Traffic Control Market Report. "Industry Urges Implementation of CPDLC Using VDL mode 2." September 27, 2002. Page 2.
[71] Air Traffic Control Market Report. "Industry Urges Implementation of CPDLC Using VDL mode 2." September 27, 2002. Page 2.

Deregulation of the Air Traffic Control Sector

The International Civil Aviation Authority (ICAO) is composed of 185 member countries whose purpose among other things is to develop the principles and techniques of international air navigation and to foster the planning and development of air transport.[72] ICAO supports air traffic control privatization, which could be more efficient, more nimble and more business-like in decision-making processing than their government run counter-parts. Consequently, it has drafted guidelines on the organization and the financial aspects of setting up these organizations. Canada and the United Kingdom are one of the original countries to privatize their air traffic control systems. [73]

The Canadians have accelerated air traffic control modernization, increased efficiency and productivity. Before privatization, air traffic controller's endured salary freezes while airlines experienced flight delays. Today, five years after privatization, NAV Canada has built three new control towers, saved airlines $163 million dollars in taxes, reduced passenger tickets by $25 dollars while increasing the salaries of air traffic controllers 33%[74] Critics of U.S. air traffic control privatization claim that the Canadian air space handles a significantly lower amount of air

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[72] International Civil Aviation Authority. Online. Internet. March 20, 2002. Available: http://www.icao.int/cgo/goto.pl?icao/en/pub/memo.htm.
[73]Poole, Robert and Butler, Viggo. How to Commercialize Air Traffic Control. Policy Study 278. Certification Issues. February 2001. Page 2.
[74]Lafaive, Michael. "Flying the Privatized Skies." Mackinac Center for Public Policy. February 1, 2000.

traffic than the United States implying that benefits in one countries air traffic control system does not necessarily translate into benefits into the other. This logic is flawed, as the main purpose of privatization is to expedite an increase in efficiency through swift deployment of modern technology at air traffic facilities.

The paradox of the U.S. policy towards air traffic control lies with the FAA. First, as the owner of the air traffic control system it is empowered with day to day operations of the system while tasked to ensure aviation safety. How likely is the FAA to monitor its own safety violations?[75]

If the U.S. would follow the path of the Canadians, then independently analyze the VDL technology without influence from existing market shareholders, it would conclude that VDL mode 4 technology is the best strategic decision for the airspace nationally and internationally.

Taxes

Due to the increased focus on aviation security from September 11, 2001, aircraft terrorist acts, a number of mandates were required aboard aircraft to provide enhanced air transport safety for air travelers. Among other things, these items required reinforced cockpit doors to prevent unauthorized entry from firearms, axes, etc. Though the cost to replace one aircraft may not be expensive, replacing an airlines fleet could

[75] Ibid.

become financial burdensome. Consequently, the U.S. congress has mandated the September 11 airline ticket tax to pay for these types of security initiatives. The airline passengers pay social cost of secure transport not to mention the psychological peace of mind that comes from knowing the cockpit is physically secured malicious passengers. Similarly, aircraft cockpit modernization expenses could be subsidized through an airline ticket tax providing safety benefits to air travelers.

National Security Interests

To prevent a repeat of the September 11, 2001 terrorist incidents, the spotlight on aviation security has risen to unprecedented levels of national security. Though it is unlikely that the perpetrator would repeat such an unspeakable act of mass destruction, the current avionics technology on board aircraft could be susceptible to an information warfare attack. For example, messages between the cockpit and air traffic control are not encoded and can be intercepted by anyone who has access to a desktop computer connected to the Internet and VHF radio. Hence, as a matter of national security, VDL technology should be implemented as its transmissions are encrypted providing an increased level of information protection.

In conclusion, VDL modes 2, 3 and 4 all fit within the allocated aeronautical radio navigation spectrum. The public policy initiatives that heavily influence the choice of VDL technology include airline incentives to promote operational deployment while mitigating the risk of these advanced technologies, passenger ticket taxes to help subsidize the costs to airliners and national security to protect airline flight operations information from being a malicious attack.

Chapter Six - Findings

Chapter one highlighted the major problems with today's air traffic control environment: airwave congestion, runway incursions and inability to get advanced weather conditions. These problems are shown in Table 6-1 along with detailed information about how we should resolve these problems.

Table 6-1 Results Comparison

PROBLEM	**DATA LINK APPLICATION SOLUTION**	**SERVICE PROVIDED**	***DATA LINK TECHNOLOGY REQUIREMENT***
Airwave voice congestion	*Communications* Controller-Pilot Data Link Communications (CPDLC)	Pilot to air traffic control communications through	VDL mode 2 VDL mode 3 VDL mode 4

		the use of data messages	
Runway Incursions	*Surveillance* Cockpit Display of Traffic Information (CDTI)	Pilot situational awareness of aircraft traffic in en-route airspace and in the terminal area.	VDL mode 4
Weather	*Communications* Graphic Weather Service	Graphical color weather displays for monitoring en-route weather.	VDL mode 2* VDL mode 4
National Security Violation	*Surveillance* Search-n-rescue	Position report of an aircraft location.	VDL mode 4

Airwave congestion

Airwave congestion can be resolved through the use of the data-link application, CPDLC, which would rely on the data link technology: VDL mode 2, 3 or 4. In high-density traffic situations, VDL mode 2 and 3 rely on random access methods, which use spectrum inefficiently and lead to ungraceful signal degradation. Therefore is not recommended for use in high-density traffic airspace(see chapter three). VDL mode 4's architecture uses spectrum efficiently, is based on an intelligent algorithm to gain access to the media, it is able to resolve conflicts quickly and tolerate high demand traffic.

Runway incursions

Runway incursions are a result of lack of situational awareness within the aircraft cockpit. By the use of a graphical display of neighboring aircraft, pilots should be able to safely navigate in the terminal area or en-route airspace. Only VDL mode 4 is capable of delivering this capability as it is available through the automatic dependent surveillance –broadcast concept.[76]

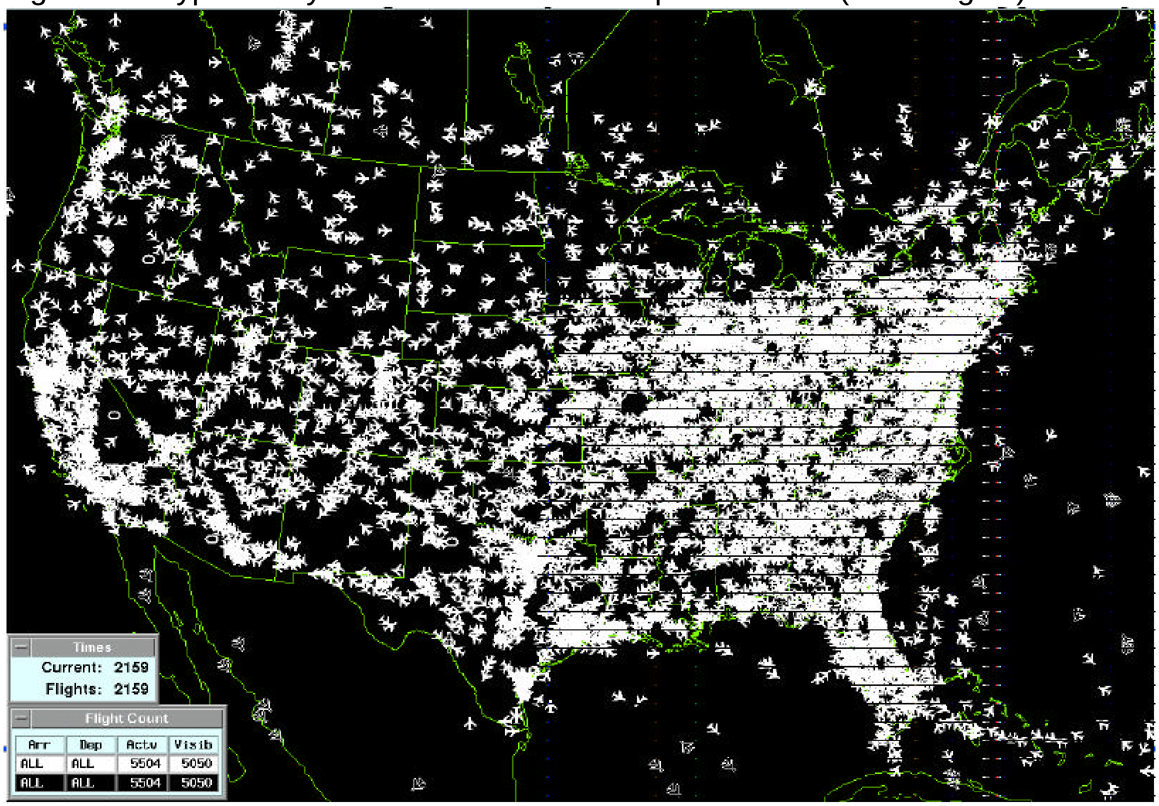
Terminal and en-route area weather updates

Weather updates for the terminal area and en-route area would best be handled by either VDL mode 4, though VDL 2 could provide service under certain restrictions. For instance, VDL mode 2 operates efficiently when there are a few aircraft in an airspace. This media access is not

[76] An aircraft obtain their positions from a GNSS receiver on-board the aircraft and transmits these coordinates over a radio data link.

conducive to high volumes of airspace traffic, which are precisely the conditions that VDL technology should withstand (see Figure 7-1).

Figure 6-1 Typical daytime United States Airspace Traffic (5500 flights) [77]



VDL mode 4 provides search and rescue capabilities that its competitors cannot provide due to design limitations. For example, in the event of a flights disappearance from radar due to disengaged transponder beacons, VDL mode 4's technology has a built-in features to address these issues. Recent FAA security initiatives could be fulfilled as through the promotion

[77] Hansman, J. Dr. The Dynamics of the Emerging Capacity Crisis in the US Air Traffic Control System Prof. R. John Hansman MIT International Center for Air Transportation Department of Aeronautics & Astronautics.

of VDL mode 4 technology. In addition, this technology could use its air-to-air features to aid neighboring aircraft in case of ground base station failures. VDL mode 4's economic costs include initial investment costs and subsequent maintenance costs to enjoy recurring benefits while VDL mode 2's and 3's return on investment is largely uncertain due to the limitations of VDL mode 2 and the anticipated transition phase from VDL mode 2 to VDL mode 3.

In conclusion, the airwave congestion problem in the U.S. needs to be addressed as it affects airline operation through timeliness of aircraft arrival, departure as well as adversely impacting the productivity of leisure and business travelers. VDL mode 4 is the best solution among its competitors, VDL mode 2 and mode 3, as it fulfills the technological requirements for current communications demand while providing a platform for future air traffic service initiatives. Chapter two (2) investigates the shortcomings of the ACARS infrastructure and its impact to the air traffic control system. ACARS low data rate coupled with a contention-based access to the media lends itself to ungraceful signal degradation in high-density airspace environments. Chapter three (3) compares and contrasts VDL modes 2, 3 and 4 through a feasibility and capability analysis as well as highlighting the main physical and data link layer characteristics. An evaluation of the economics of air to ground communications both for aviation electronics (avionics) costs in commercial airline cockpits and ground-based infrastructure costs is provided in chapter four (4). Lastly, chapter five (5) evaluates the public policy implications that could promote or inhibit the VDL technologies while chapter six (6) recommends VDL technology mode 4 based on current requirements, modern technology and available economic data. The public policy initiatives that heavily influence the choice of VDL technology include airline incentives to promote operational deployment.

These chapters support my hypothesis that the VDL mode 4 is the superior data link technology. First, this platform provides a superior communication and navigation benefit over its rivals VDL mode 2 and 3. Second, VDL mode 4 lends itself to situational awareness applications that could be seamlessly integrated into a variety of VDL applications such as CDTI and enroute weather applications. Clearly, VDL mode 4 is scaleable and enables the advancement of future air traffic control initiatives.

Future Research

A migration path from ACARS to VDL mode 4 should be investigated as it would be needed should the U.S. decide to change its argument for VDL mode 2. This investigation should focus on the ability to make a transition with out destroying the current ACARS network.

Also, the security aspects of VDL mode 2 and VDL mode 4 should be further developed to analyze the vulnerabilities of these systems. Specifically, with the continued migration towards the information aged flight operations environment, pilots could eventually trade in their bulky flight bags for laptops. These laptops would have a variety of uses such as providing an intuitive interface to upload/download flight planning data with onboard avionics. These routine activities could become a national security risk as the probability flight operations information interception could evolve into a new ground for terrorist activity. A malicious passenger could through the use of a laptop computer, intercept and manipulate aircraft settings such as flap settings, speed, altimeter settings affecting aircraft take offs and landings, the most vulnerable phases of a flight.

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